REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. REPORT DATE *(DD-MM-YYYY)*
27/04/2009

2. REPORT TYPE
Final

3. DATES COVERED *(From - To)*
10/24/2008-04/27/2009

4. TITLE AND SUBTITLE
Tethered Antennas for Unmanned Underwater Vehicles

5a. CONTRACT NUMBER
N00014-09-M-0038

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)
Race, Roger, E.
Piskura, Jacob C.

5d. PROJECT NUMBER

5e. TASK NUMBER

5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
Brooke Ocean Technology, USA
1213 Purchase Street
New Bedford, MA 02740

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
Office of Naval Research
Robert H. Headrick Jr, ONR Code 321
One Liberty Center
875 North Randolph Street
Arlington, VA 22203-1995

10. SPONSOR/MONITOR'S ACRONYM(S)

11. SPONSORING/MONITORING AGENCY REPORT NUMBER

12. DISTRIBUTION AVAILABILITY STATEMENT
Approved for public release; SBIR report, distribution unlimited.

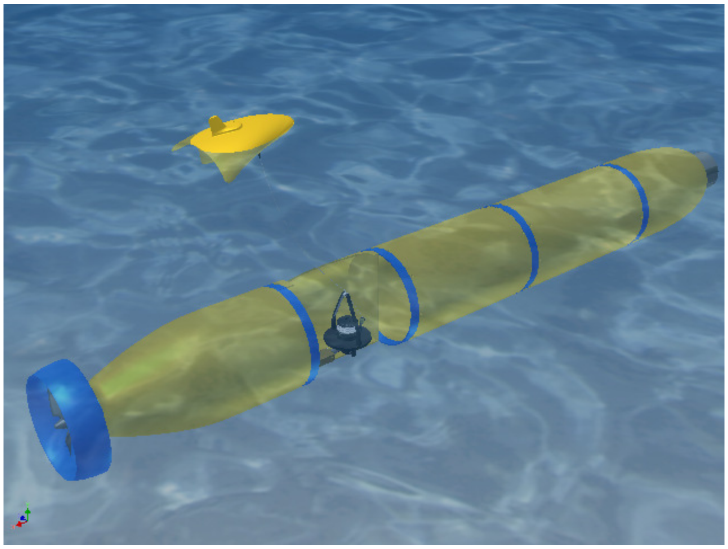
13. SUPPLEMENTARY NOTES

14. ABSTRACT
The Small Business Innovation Research (SBIR) Program has funded the development of a system that will allow UUVs to communicate through RF communication and collect GPS location while below the surface and travelling at speed. Under this effort, Brooke Ocean Technology USA, Inc. (BOT USA) has conducted a Phase I study to develop, evaluate, and select innovative concepts for a Towed Antenna System (TAS). Based on this study, a functional proof of concept tow body has been built and tested. Both GPS and Wi-Fi were successfully demonstrated at sea while the system was under tow. An innovative launch and recovery reeling system has been designed and the key elements of the system have been tested. Going beyond the proof of concept, BOT USA has created a set of optimized design concepts for consideration in the final system. The work conducted to date would significantly reduce the risks associated with building a functional TAS system in a Phase II program. In addition, successful creation of a universal towed antenna would be of interest to the ever-growing world of commercial UUVs in use today. BOT USA is in a unique position to capitalize on this large market opportunity.

15. SUBJECT TERMS
AUV, GPS, towed antenna, WIFI, real time communications underwater

16. SECURITY CLASSIFICATION OF: a. REPORT	b. ABSTRACT	c. THIS PAGE	17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
Unclassified	Unclassified	Unclassified	UU	36	Lois Prevett-McCarthy
					19b. TELEPONE NUMBER (*Include area code*) 508-990-4575

Phase I Final Report
0001AC



U.S. DEPARTMENT OF DEFENSE
NAVY SMALL BUSINESS INNOVATION RESEARCH (SBIR) PROGRAM
REPORT COVER SHEET

April 27, 2009

TOPIC NUMBER: **N08-194**
CONTRACT NUMBER: **N00014-09-M0038**
PROPOSAL TITLE: **Tethered Antennas for Unmanned Underwater Vehicles**

FIRM NAME: **Brooke Ocean Technology, USA**
MAIL ADDRESS: **1213 Purchase St.**
New Bedford, MA 02740

PERIOD COVERED: **Project end date – April 27, 2009**

Technical POC: **Roger Race**
(508) 990-4575
(rrace@brooke-oceanusa.com)

Business POC: **Lois Prevett-McCarthy**
508) 990-4575
(lprevettmccarthy@brooke-oceanusa.com)

Abstract

The U.S. Department of Defense has created a Small Business Innovation Research (SBIR) Program to develop systems that will allow UUVs to communicate through RF communication and collect GPS location while 3 to 5 meters (m) below the surface and travelling at 2 to 3 knots. Under this effort, Brooke Ocean Technology USA, Inc. (BOT USA) has conducted a study to develop, evaluate, and select innovative concepts for a Towed Antenna System (TAS). Based on this study, a functional proof of concept tow body has been built and tested. Both GPS and Wi-Fi were successfully demonstrated at sea while the system was under tow. An innovative launch and recovery system has been designed and the key elements of the system have been tested. Going beyond the proof of concept, BOT USA has created a set of detailed optimized design concepts for consideration in the final system. We feel the work conducted to date would significantly reduce the risks associated with building a fully functional TAS system in a Phase II program. In addition, successful creation of a universal towed antenna would be of great interest to the ever-growing number of commercial UUV users around the world. BOT USA is in a unique position to capitalize on this large market opportunity.

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1.0 INTRODUCTION

Current Unmanned Underwater Vehicles (UUVs) are not able to communicate or determine their exact location while conducting missions underwater. In order to use GPS or RF communications, they must reach the surface where they are unstable, have reduced steerage, and can not collect mission data. This greatly reduces the operational effectiveness of the UUV. To solve this problem, the U.S. Department of Defense has created a Small Business Innovation Research (SBIR) Program to develop systems that will allow UUVs to communicate through RF communication and collect GPS location while 3 to 5 m below the surface and travelling at 2 to 3 knots. Under this effort, Brooke Ocean Technology USA (BOT USA) Inc., with support from Bluefin Robotics Corp. (Bluefin), is conducting a study to develop, evaluate, and select innovative concepts for a Towed Antenna System (TAS). The success of this program will be derived from the combination of BOT USA's experience with tow bodies and Bluefin's experience in underwater vehicles and communications.

1.1 Background

When a UUV is underwater it cannot receive a GPS signal and it cannot communicate utilizing radio. This is a problem for all users of UUVs. The ability to communicate rapidly and in real time while still submerged could be very beneficial to many applications, the Terminal Swimmer Detection and Targeting (TSDT) Future Naval Capability (FNC) application in particular. A tethered antenna that will support two-way RF communication and GPS reception would greatly enhance the ID and localization capabilities of all UUVs. The added advantage is the UUV with a towed antenna will be much more maneuverable underwater in 3 or 5 m than it would be on the surface. In addition, successful creation of a universal towed antenna will be of great interest to the ever-growing number of users of autonomous vehicles around the world.

1.2 Commercialization Potential

BOT USA would utilize our network connection to the oceanographic world to promote the new (TAS). We have a popular web site www.brooke-oceanusa.com and a travel schedule to ocean shows, both of which would lead to excellent exposure of this new technology. We also have a multitude of direct contacts throughout the industry to which we can send emails and letters announcing this new device.

BOT USA will promote this technology with targeted advertising in selected trade journals, news releases, web pages, and publishing of technical papers. This device fits well with BOT USA's products. Existing marketing and distribution networks will be utilized to promote and sell this product. This will be augmented with attendance at domestic and international ocean trade shows.

Initially, the domestic US Navy market will be targeted. This would include actively promoting this system to US Navy stakeholders with existing UUVs. With that in mind, we have received a letter of support from Lockheed Martin Sippican, indicating that they would be very interested in working with BOT USA on a Phase II to develop a commercially viable TAS system. The letter from Wolfgang Schlegel the head of Underwater Vehicles Division of LMS is attached at the end of this report. Following that would be the commercial users of UUVs. There are hundreds of UUVs in use today, that number is expected to grow into the thousands within a decade, and all autonomous vehicle users can benefit from the accuracy and two-way real time communication available from our towed system.

2.0 DESIGN REQUIREMENTS

A list of design requirements was created from those specified in the SBIR as well as those from Bluefin engineers that dictated what was within operational requirements of their 12 ¾ in. UUVs. These requirements were refined through two meetings at Bluefin Robotics Corp. located in Cambridge, Massachusetts.

Typical UUV missions can last up to 18 hours in duration, during which it is desired that the TAS provide between 20 and 50 deployments, each lasting from 3 to 8 minutes. Since Iridium transmission can draw up to 20 watts of power, the resulting maximum capacity is 133 watt-hours of energy. Therefore, the system will either require a battery with 133 watt-hour capacity, or an electro-mechanical tow cable that can carry 20 watts from the UUV's batteries.

2.1 GPS & Communication System

In order to be an effective asset, the system must provide consistent GPS location data and reliable two-way RF communication. In the case of GPS and Iridium, the targets are satellites in the overhead sky. As long as the antenna is above the water it should have no problem obtaining signals for both these sources. Short-range communication such as Wi-Fi and 900 MHz spread-spectrum will be more susceptible to effects from splash over and the antenna dipping beneath nearby waves. It may be necessary to raise the RF antennas up in order to get acceptable performance in any kind of rough sea condition.

2.2 Tow Body

The requirements of the tow body portion of the system are that it has minimal impact on the buoyancy and overall hydrodynamics of the Bluefin UUV. It must contain all the necessary electronics and batteries if necessary. When deployed, it is very important that the tow body reaches the surface, otherwise it is useless. To accomplish this it needs to have a lift to drag ratio much greater than 1. In this case lift is defined as the sum of hydrodynamic lift and buoyancy. Once at the surface it must be stable and allow the communications to work consistently.

2.3. Tow Cable

The tow cable that is to be used must support multiple two-way communications; transmitting the GPS data as well as the two-way data communication, while having minimal drag. The cable must be long enough for the UUV to operate at 3 to 5 m below the surface with the tow body on the surface. Strength members in the cable should allow the cable to survive the tensions associated with towing at 5 knots as well as any snags that it may encounter.

2.4 Launch and Recovery System

The launch and recovery system (LARS) needs to be small, simple, low cost, and be able to reliably launch and recover the tow body throughout the entire UUV mission. To accomplish these goals, an innovative winch design with no slip ring must be developed. The receptacle that the TAS will nest should allow quick and easy departure during launch and reliable nesting and locking after recovery. While the TAS is stowed in the receptacle there should be minimal surfaces exposed to the flow in order to minimize disturbances on the UUV.

3.0 PROOF OF CONCEPT

In order to minimize the risks associated with designing an entire system on paper, many of the concepts that were developed were actually built and tested. A full-scale tow body was created and fitted with GPS and Wi-Fi modules. A tow cable that carried power and data was fit into the tow body and connected to the electronics inside. The other end of the cable was plugged into a laptop computer which was used to simulate the UUV's computer. Testing was carried out in a small motor boat while the TAS was towed from a pole held over the side. Some elements of the launch and recovery system were built and tested as well. Building and testing gave us tremendous insight into the performance traits, both good and bad, of each system element. This led to an optimized set of design concepts for a future version of the TAS.

3.1 Tow Body

The design of the tow body was approached from two different ways. After a series of iterations based on feedback between the engineers of BOT USA, two half scale models were created using Stereolithography (SLA) to see what the pros and cons of each design were when actually put in the water and towed. Through the use of a test tank, quantitative and qualitative measurements were done to evaluate the performance characteristics of each model and a winner was selected. From this, a design iteration process was done to further develop and refine the design. The next step in the process was to have a full scale model constructed using SLA. Real world testing was done on the body at speeds up to 4 knots to see how the body reacted in the ocean.

3.1.1 Tow Body Initial Concepts

The first design (Figure 1) was based on the concept of an airfoil kite. The shape of the tow body was built around a NACA5515 hydrofoil to provide hydrodynamic lift while a V-shaped pod on the underside of the wing was added to provide more volume for buoyancy and to make room for the electronics. A strip with multiple tow points was added to the bottom since the optimal tow point needed to be determined through testing. As stated in section 2.2, one of the design goals was to have minimal affect on the hydrodynamics of the UUV when in the stowed position. To accomplish this, the top profile was designed to match the shape of the 12 ¾ in. UUV, (Figure 1b). When the tow body is stowed it will fit into a special receptacle cut into the UUV's hull. The only parts exposed to the flow will be the conformal top surface. This will allow the UUV to function as normal during times when the TAS is stowed – which could be up to 94% of the mission time.

Figure 1: Hydrofoil Design

The second design was based on that of a boat hull (Figure 2). The hull was designed with a “deep V” to allow for straight tracking when on the surface as well as providing a stable platform for communications. A sharp bow was utilized to cut through the water to reduce drag when on the surface. Like the hydrofoil design the top profile was made to be conformal with the body of the UUV to reduce drag when the system is not in use. The focus of this design was the performance when on the surface. An access panel with a GPS blister mounted on it allows for easy access to the electronics and moving of the ballast to find an optimal center of gravity for the tow body. A series of holes was made in the keel to allow for towing from multiple locations to find the optimal tow point.

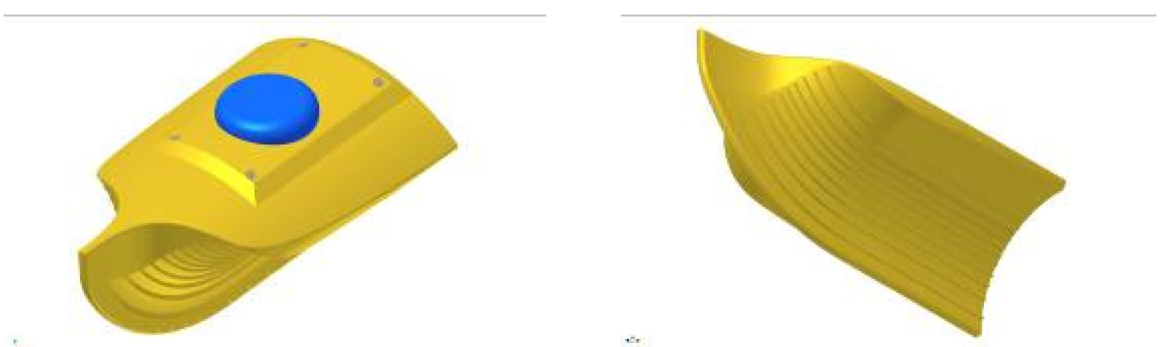

Figure 2: Boat Hull Design

3.1.2 Half Scale Model Testing

The two tow body SLA models (Figure 3) were tested at the SMAST test tank.

Figure 3: Left – Hydrofoil Tow Body Model & Right – Boat Hull Tow Body Model

The models were towed behind a small radio controlled UUV to see how they performed beneath the surface and on the surface (Figure 4). A small monofilament line was used to simulate the tow cable. Both models were made with an adjustable tow point. By adjusting the tow point the tow bodies' attitudes could be adjusted for optimal flight through the water.

Figure 4: Models Being Tow Tested

3.1.3 Half Scale Model Testing Results

Table 1: Pros and Cons of the Two Tow Body Designs

OPTION	PROS	CONS
Hydrofoil Tow Body	• Stable on surface • Stable underwater • Tracked well in turns	• Straight line performance was slightly wavy due to lack of keel • Cannot provide much payload capacity • Nose dug in slightly rather than gliding over surface
Boat Hull Tow Body	• Tracks on surface well in a straight line, bow up • Towed well underwater in a straight line • Provides slightly more payload capacity than hydrofoil design	• Unstable in turns due to sharp bow • Hydrodynamic lift minimal, mainly relies on buoyancy • Rolls and twists when turning underwater

3.1.4 Full Scale Model

From these results, it was determined that the hydrofoil was the better design. Further refinements were made to solve the cons and a full scale model of that design was produced (Figure 5).

Figure 5: Full Scale SLA Model

To address the shortcomings of the previous hydrofoil tow body, three things were changed for the full scale model. First, a fin was placed on the bottom of the tow body towards the stern. This will improve the straight-line tracking of the body in the same way as a rudder would act on a boat. Second, the body's chord length was increased from 10 in. to 12 in. This increased the body's volume by 40% and therefore gave it 40% more buoyancy or payload capacity. Lastly, the nose was adjusted so it would plane over the water's surface better, rather than digging in. To facilitate the mounting of the electronics inside, a sealed hatch was added the top of the tow body. Small machine screws and an O-ring keep the hatch lid secured and watertight. We feel this design builds upon the success of the first generation hydrofoil body and should offer a streamlined and stable platform for the TAS electronics.

3.2 Tow Cable

System testing was done on April 9, 2009 in Padanaram harbor located in South Dartmouth, Massachusetts. I M2-220 (Figure 6) made by Opticis Co. was used. It is an integrated USB fiber optic link with power over copper as well. The M2-220 has a large diameter (0.26 in.) which increased drag forces in testing, but the plug and play aspects of it make it very attractive for simple concept testing.

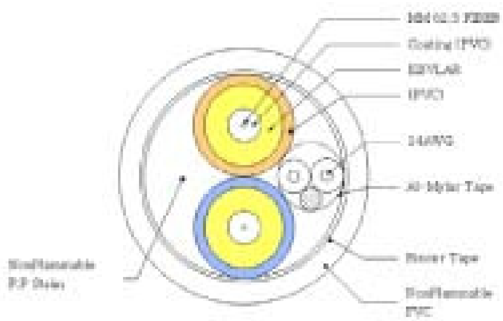

Figure 6: M2-220 Fiber Optic Cable

For the test, the M2-220 was integrated into the tow body. It was installed into the tow body by cutting out a small section of the bottom of the hull to allow for the cable's integrated hardware to go inside the body. The removed section of the tow body was epoxied back in place with the cable running through it. The cable was then epoxied both inside and outside of the hull to ensure that is would not slip while being towed. A flexible polysulfide strain relief was added to ensure no water would enter the tow body (Figure 7). The end of the tow cable was then plugged into a USB hub that GPS and Wi-Fi data could then be transmitted through. The cable then ran around a sheave 6 feet under water and up to a computer. This allowed the tow body characteristics in water to be seen while being towed between 1 and 4 knots in 0 to 6 in. waves. Strumming of the cable as well as drag was high during towing and the use of a smaller diameter cable for future testing will greatly improve the tow cable design.

Figure 7: Fiber Optic Cable integrated into Tow Body

3.3 Electronics Package

For proof of concept, the electronics package tested in this SBIR was focused on GPS location and RF communication. The GPS unit and RF unit were potted into the blistered top section of the tow body (Figure 8). Each unit first had the plastic casing removed.

Figure 8: GPS and Wi-Fi Chips Potted into the Tow Body

3.3.1 GPS Hardware

The GPS location system consists of a GlobalSat SiRF III transceiver module (Figure 9) that was potted to make it suitable for underwater use. This commercial off the shelf (COTS) device is inexpensive and communicates via USB. Up to 20 parallel satellites can be tracked at once due to its high performance SiRF Star III chipset. Data is output in standard NMEA 0183 format over the USB interface.

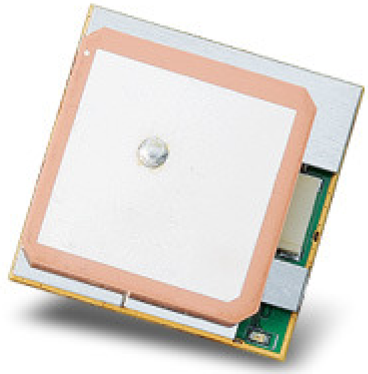

Figure 9: GlobalSat SiRF III GPS Module

3.3.2 GPS Testing

For testing, the Tow Body was towed around Padanaram harbor on April 9, 2009. Several experiments were done during testing. In the first test, GPS data was collected and input into a Google Earth to chart the path of the tow body as it was towed by a skiff around a small island located in the harbor (Figure 10).

Figure 10: Tow Body Path

From the image, it can be seen that the path of the tow body was consistent without any outlying data points.

The next test of the GPS system was to slowly force the tow body underwater while recording GPS data to determine when the receiver lost satellite reception. It was found that reception was lost when submerged more than 1 inch and satellites were reacquired in seconds once the tow body was returned to the surface.

3.3.3 RF Communication Hardware

The RF communication used for this project is a Wi-Fi based communication rather then spread-spectrum. For prototype work, a Wi-Fi transceiver module based on the RTL8187B chipset (Figure 11) is being used. This module operates with the standard IEEE 802.11g protocol which provides a range of approximately 100 m.

Figure 11: Trendnet TEW-424UB Wi-Fi Module

3.3.4 RF Communication Testing

A test of the TAS Wi-Fi range was conducted on March 26, 2009. In the test, the tow body was placed in the water along side a dock in Padanaram harbor. A battery powered router was carried through the four sites shown in the map (Figure 12).

Figure 12: Wi-Fi Test Map

It was carried at waist level and at about every 30 ft it was held over the side of the bridge. That is why the signal to noise ratio (SNR) has such dramatic peaks and valleys (Figure 13). The approximate height of the router off the water was 12 ft. At sites 3 and 4 the body was towed around behind a pole. A higher SNR means better signal quality.

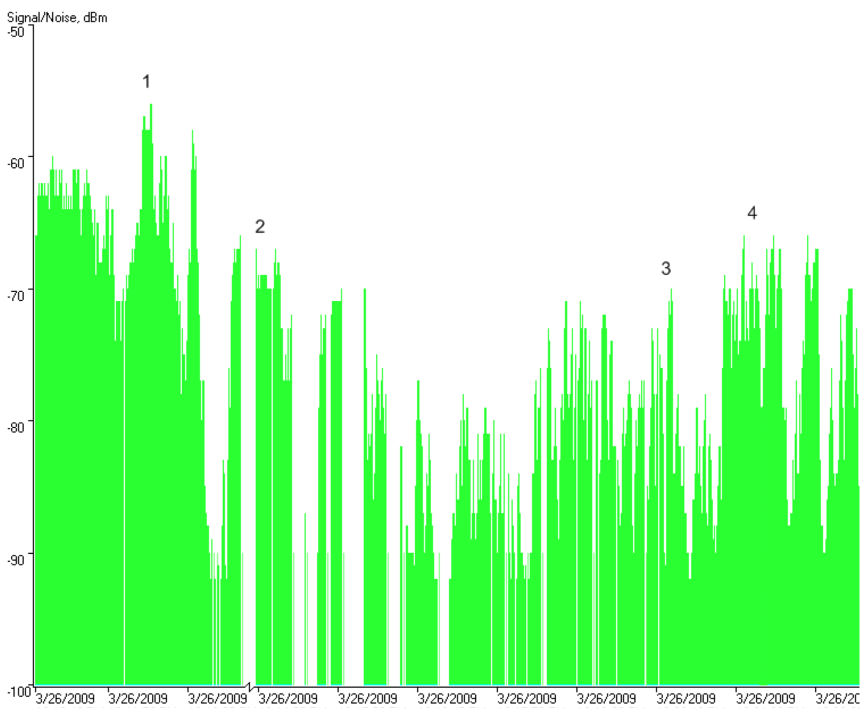

Figure 13: Signal to Noise Ratio Results

Sample ping results while towing at site 3 are shown here. There is a lot of latency as well as frequent dropouts.

```
Reply from 192.168.2.1: bytes=32 time=3028ms TTL=64
Reply from 192.168.2.1: bytes=32 time=33ms TTL=64
Reply from 192.168.2.1: bytes=32 time=17ms TTL=64
Request timed out.
Reply from 192.168.2.1: bytes=32 time=525ms TTL=64
Request timed out.
Reply from 192.168.2.1: bytes=32 time=526ms TTL=64
Reply from 192.168.2.1: bytes=32 time=526ms TTL=64
Reply from 192.168.2.1: bytes=32 time=522ms TTL=64
Reply from 192.168.2.1: bytes=32 time=523ms TTL=64
Request timed out.
Reply from 192.168.2.1: bytes=32 time=524ms TTL=64
Reply from 192.168.2.1: bytes=32 time=523ms TTL=64
Request timed out.
Reply from 192.168.2.1: bytes=32 time=524ms TTL=64
Reply from 192.168.2.1: bytes=32 time=523ms TTL=64
Reply from 192.168.2.1: bytes=32 time=522ms TTL=64
Reply from 192.168.2.1: bytes=32 time=523ms TTL=64
Reply from 192.168.2.1: bytes=32 time=533ms TTL=64
Request timed out.
Reply from 192.168.2.1: bytes=32 time=3678ms TTL=64
Request timed out.
```

Sample ping results while towing at site 4 are shown here. Latency is steady and at acceptable levels and there were no dropouts for the duration of the site test.

```
Reply from 192.168.2.1: bytes=32 time=54ms TTL=64
Reply from 192.168.2.1: bytes=32 time=54ms TTL=64
Reply from 192.168.2.1: bytes=32 time=53ms TTL=64
Reply from 192.168.2.1: bytes=32 time=57ms TTL=64
Reply from 192.168.2.1: bytes=32 time=53ms TTL=64
Reply from 192.168.2.1: bytes=32 time=53ms TTL=64
Reply from 192.168.2.1: bytes=32 time=54ms TTL=64
Reply from 192.168.2.1: bytes=32 time=53ms TTL=64
Reply from 192.168.2.1: bytes=32 time=54ms TTL=64
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 Reply from 192.168.2.1: bytes=32 time=53ms TTL=64
Reply from 192.168.2.1: bytes=32 time=53ms TTL=64
Reply from 192.168.2.1: bytes=32 time=55ms TTL=64
Reply from 192.168.2.1: bytes=32 time=53ms TTL=64
```

GPS testing was done by towing the body behind a pole and monitoring the string of NMEA data coming in from the module. The following sentences show the unit had a successful fix on satellites.

```
$GPGGA,165837.000,4135.1941,N,07056.7651,W,2,11,0.9,6.4,M,-34.4,M,0.8,0000*4F
$GPGSA,A,3,08,10,09,27,26,18,15,24,21,29,02,,1.3,0.9,1.0*38
$GPRMC,165837.000,A,4135.1941,N,07056.7651,W,0.19,175.92,260309,,*1E
$GPGGA,165838.000,4135.1941,N,07056.7651,W,2,11,0.9,6.4,M,-34.4,M,0.8,0000*40
$GPGSA,A,3,08,10,09,27,26,18,15,24,21,29,02,,1.3,0.9,1.0*38
$GPRMC,165838.000,A,4135.1941,N,07056.7651,W,0.07,65.49,260309,,*28
```

```
$GPGGA,165839.000,4135.1941,N,07056.7651,W,2,11,0.9,6.4,M,-34.4,M,0.8,0000*41
$GPGSA,A,3,08,10,09,27,26,18,15,24,21,29,02,,1.3,0.9,1.0*38
$GPRMC,165839.000,A,4135.1941,N,07056.7651,W,0.06,202.70,260309,,*11
$GPGGA,165840.000,4135.1941,N,07056.7650,W,2,11,0.9,6.5,M,-34.4,M,1.8,0000*4E
```

When the unit lost fix the sentences had lots of empty fields like this.

```
$GPGGA, 165837.000,,,,,0,0,99.99,,,,,,*5F
$GPRMC,165837.000,A,,,,,,,N,,,,,,,,W,0.19,,,,,,260309,,*1E
```

This made it easy to spot the moments it lost a fix and then regained it. Typically, we observed the unit maintaining a GPS fix until it was submerged more than about 1 in. Less than 1 in. seemed fine. Then when the body was allowed to surface the fix was regained within 2 seconds.

From these results, the Wi-Fi seems to loose its effectiveness at approximately 225 ft, with the short dorsal mount.

3.4 Harbor Testing Full Scale Body

On December 15th, a tow test of the new model was done in Padanaram harbor. The tow body was attached to a small fish weighing scale for measurements and towed along side a small skiff (Figure 14). A pole that the tow line was attached to was held over the side of the skiff. The results of the tow test were that at 2 knots there was 4 ounces of drag, at 2.2 knots there was 5 ounces of drag and at 2.8 knots there was 7 ounces of drag. These drag forces were in the range of what we had calculated. The tow body fulfilled many of the short comings of the previous half scale model. The nose design allowed the tow body to stay at the surface and plane over the water as it was towed between 1.5 and 4 knots. There were times that the nose did dig into the trough of the waves as it came down the front of the previous wave. The body would submerge for a few seconds and then the lift from the hydrofoil would drive it back to the surface. An improvement for the next tow test will be to move the ballast more aft to provide more buoyancy to the nose of the body. The keel greatly improved the straight line track of the body.

Figure 14: Full Scale Tow Body Being Tested at 2 Knots Dec. 15, 2009

On April 9, 2009 the body was tested again under tow in Padanaram harbor (Figure 15). This time, the body was towed from a point located 6 ft under water and towed at 1 to 4 knots. It was towed into, a beam to, and running with small waves, 0 to 6 in., to test its towing characterizes with a revised top cover and electronics potted into it. The testing found that at 2 knots and above, the hull appeared to plane off and it drove over the waves well with its bow up and minimal wash over the top of it.

Figure 15: Full Scale Tow Body Being Tested at 1 Knot Apr. 9, 2009

4.0 SYSTEM DESIGN

The system that was built for this Phase I study was designed for low cost and relative ease of fabrication while still providing a real proof of concept. Moving forward, several aspects of the system could be optimized to provide enhanced functionality and higher efficiency. BOT USA has identified these aspects and optimized them through the use of state-of-the-art ideas and components.

4.1 Tow Body

Based on the testing performed at sea, we feel the current tow body design meets all of our goals performance-wise. Stability and tracking were extremely good as was GPS reception. The location of the tow point allows the bow to travel over the tops of the waves rather than through, keeping the area where the antennas are mounted from having too much wash over. The body has been designed to be conformal to a 12 ¾ in. UUV minimizing its influence on the UUV while stowed. The wing shape of the body provides a stable platform for Wi-Fi communication and GPS positioning. The V-shape causes it to be a planing hull rather than a displacement hull at speed over 2 knots which reduces drag.

Improvements will need to be made in the construction of the body to allow easier fabrication. The current tow body was fabricated by SLA. This technology is great for rapidly assessing different designs but is impractical for actual production. Slight changes will be made to the design that will allow it to be produced in molded plastic. This will also produce a more rugged body than the SLA version. The top hatch will most likely be eliminated. It was designed to allow easy access to the electronics for making changes; however, the final product should not need to be changed once it is built. This also eliminates the risk of the hatch leaking.

The split design will stay as it is since this allows the body to be modular to fit different antenna types. We can keep the bottom half the same and produce different variants of the top half. Depending on the customer's needs, the appropriate top half and associated electronics will be fitted. For example, the current top with the antenna blisters (Figure 16a) would work well in a harbor situation where waves will not be very large. For higher sea states out in open water a mast (Figure 16b) can be used to raise the antennas away from the surface. The halves will be bonded and sealed to make sure no water enters the cavity and also to prevent tampering.

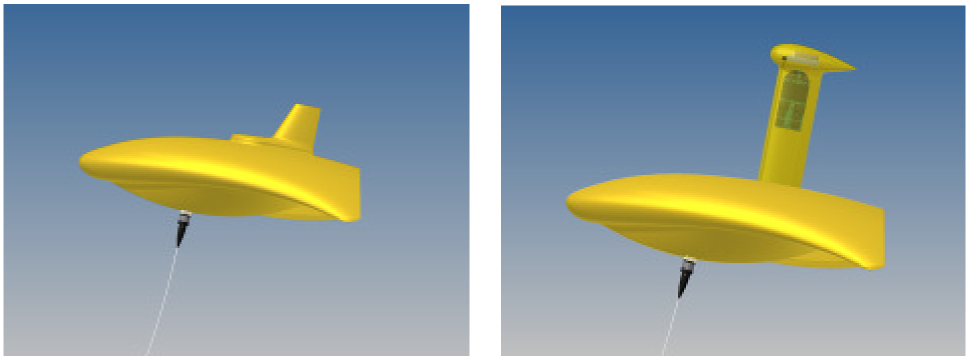

Figure 16: TAS with Blister Antenna and Mast Antenna

A flat area will be added where the tow cable connector is installed. This will allow us to use COTS underwater connectors with an o-ring face seal. A backing nut on the inside will keep the connector rigid and watertight.

4.2 Tow Cable

The selection of the tow cable is extremely important since it affects the towing performance so greatly. We need a small diameter cable capable of transmitting power and data and strong enough to tow a load through the water. Two options are being considered that will meet these goals. The first option is a 3 mm duplex fiber optic cable with a Kevlar strength member. The second is a 1.2 mm coaxial cable with a silver plated steel core and copper shielding.

4.2.1 Fiber Optics Option

Fiber optics are becoming more and more popular for situations requiring long cable runs and/or extremely high bandwidth. They offer unmatched performance in both of these areas, but they also have the advantage of being very compact due to the fact that multiple data streams can be multiplexed onto a single fiber. This trait makes them attractive for this project because of the importance of having a small diameter tow cable. Some disadvantages are that the components are typically very expensive and if things go wrong it can be very difficult to bring the system back into operation.

We have explored several options for using fiber optics as our tow body to UUV interface. The first option is a COTS duplex fiber optic cable with a Kevlar strength member and waterproof PVC jacket made for terrestrial fiber optic cable runs (Figure 17).

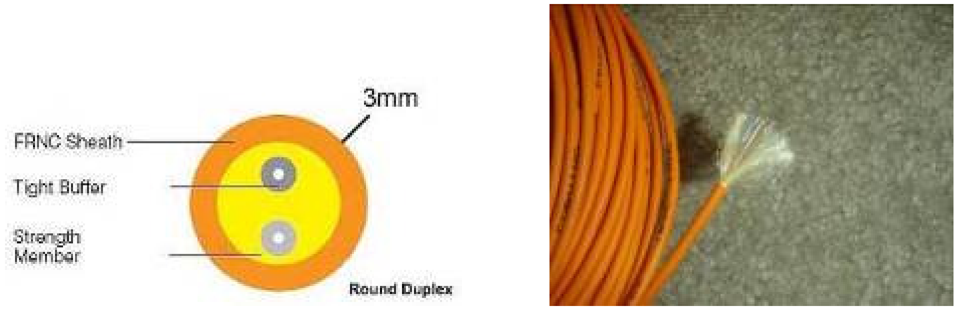

Figure 17: COTS Round Duplex Tow Cable

The second is a custom marine tow cable with three optical fibers incased in a gel filled stainless steel sheath surrounded by Kevlar and a polyurethane jacket (Figure 18). The reason for using three fibers is to maintain circular symmetry in the stainless steel sheath. Both cables are 3 mm (0.12 in) in diameter. The COTS cable has the advantage of being very inexpensive while the custom cable should be more rugged in a rough marine environment.

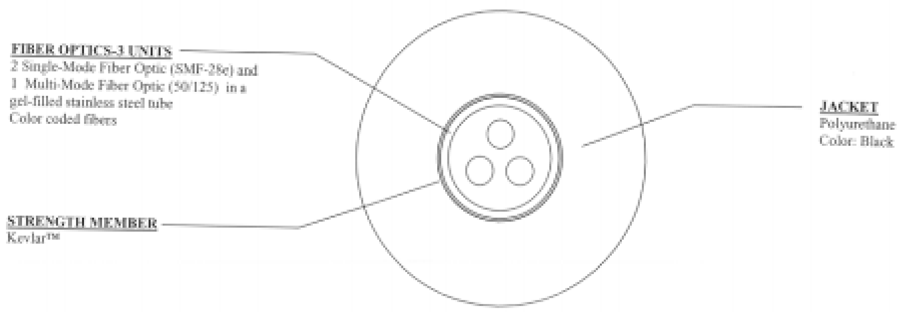

Figure 18: Custom Round 3-Fiber Tow Cable

The cables were simulated with the UUV at 9ft depth (Figure 19). The results below show that the tow body is able to reach the surface for all speeds analyzed. Since both cables have the same diameter the catenary results will be the same.

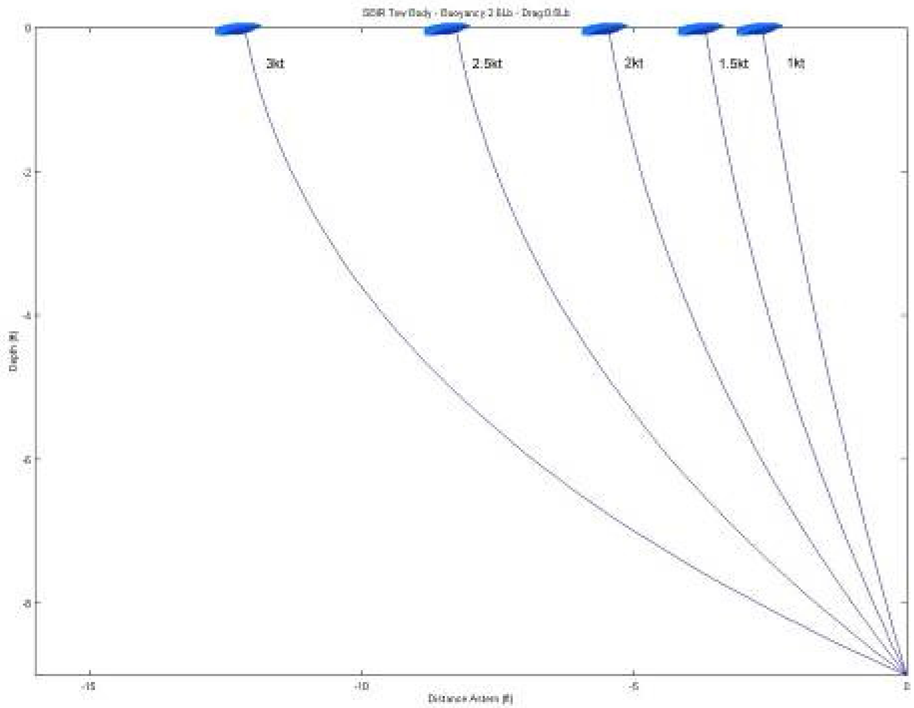

Figure 19: 3mm Tow Cable Depth vs. Distance Astern at Different Speeds with UUV at Depth of 9 Ft

A study was conducted to determine the maximum operational depth of the system. Results show that a depth of 30 ft is possible at speeds up to 2 knots.

4.2.2 Coaxial Cable Option

We have also considered using a copper coax cable for the tow cable. This option presents some substantial advantages over fiber optics. First, coax cables can be made even smaller than fiber optic cables. As mentioned earlier, a smaller tow cable results in greater depth and speed envelopes for the UUV meaning less of an impact on ConOps. Second, electrical components are typically orders of magnitude less expensive than their fiber optic counterparts. Lastly, copper systems are much more rugged than fiber optics which results in less down time, less repair operations and better monitoring of operational status.

A miniature coax cable was sourced with a 0.046 in. diameter (Figure 20). It has a 34awg silver plated steel conductor, tinned copper shielding and FEP jacket. This cable can support up to 600 volts and 0.2 amps. Since the current is so low we will need to step up the voltage to provide enough power for the electronics. By adding a filter we can also send data along the same wire. Our idea is to use the conductor as one wire and the shield as a second wire. This will allow us to use a two-wire protocol to send data over the tiny tow cable. The minimum bend radius for this cable is not published, however standard practice calls for 15 times the diameter, or 0.7 in. Break strength was measured to be 10Lb. We expect the maximum tension to be 3Lb so this cable will have a 3:1 safety factor.

Figure 20: Mini Coax Tow Cable

The coax cable was simulated in the catenary program. This cable has very good towing characteristics as seen in the graph below (Figure 21). With this cable deeper deployments and higher speeds will be possible than with any other cable we have considered.

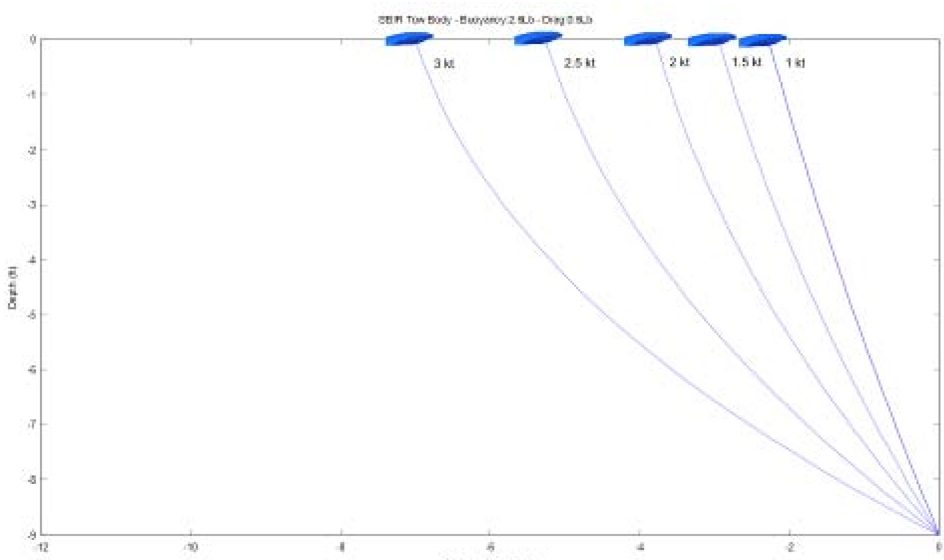

Figure 21: Mini Coax Tow Cable Depth vs. Distance Astern at Different Speeds with UUV at Depth of 9 Ft

4.3 Electronics and Instrumentation

We have chosen the approach of making the TAS a self contained communications system rather than just a passive antenna. The reason for this is that we can have multiple communications sources operating at the same time instead of just one. Also we can process the data onboard and send it down the cable as a digital signal. This eliminates any risks of sending RF signals over a long tow cable since the attenuation is quite high. The tow body will have GPS, Iridium and Wi-Fi devices installed and a small microcontroller will feed the data from all three down the tow cable.

4.3.1 Electronics Interface

4.3.1.1 Fiber Optic Cable

The fiber optic interface has been researched and two different options have been considered. The first option is to use a PRIZM Ultimate USB (Figure 22) fiber optic link. This offers bi-directional communication with a 4 port USB 1.1 hub over a single fiber. This is all done on a single compact card. The drawbacks are that it is expensive, requires up to 7.5 watts of power, and limits the type of communications hardware to just USB. Two boards are required for the system to be complete; one board for each side of the fiber optic wire. The Ultimate USB is 3.7 in. by 3.6 in. by 0.65 in. in size, standard PC104 form factor, and costs about $3000 for a complete system.

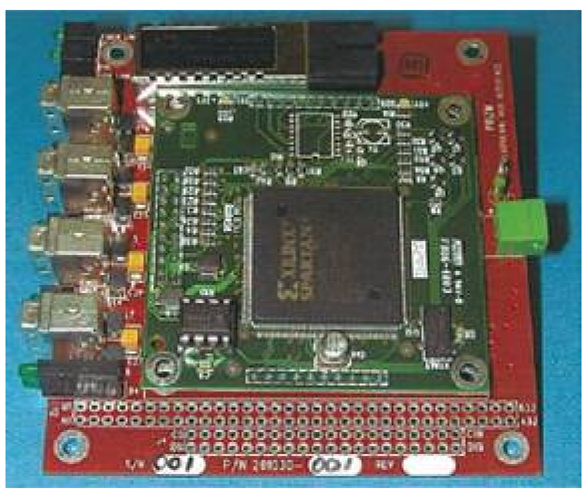

Figure 22: PRIZM Ultimate USB

Another option being considered is to use an Axcen Photonics Corp. AXFT-1621 (Figure 23) single fiber bi-directional receptacle/ transceiver. The module is 1in. by 1.56 in. by 0.38 in. in size and sells for about $20. The advantage of this design is that is can take signals at the serial TTL level making it compatible with virtually any type of communications hardware. A second multiplexer board would be required that combines the signals from the different instruments. The transceiver requires custom supporting circuitry in order to operate but this board could incorporate the additional multiplexers and provide breakouts for communications ports to attach additional communication modules.

Figure 23: Axcen Photonics Corp. AXFT-1621 125 Mbps Single Fiber Bi-directional Transceiver

4.3.1.2 Coaxial Cable

The interface over coax cable consists of two parts. The first combines the signals from multiple sources and sends them over a single bus. The second allows transmitting the data in both directions over two wires. Since coax is essentially two wires (conductor and shield) it should be possible to use a two-wire protocol to communicate effectively over the cable.

A Gumstix microprocessor could be used to combine multiple signals and send them over a single bus. The Gumstix Verdex Pro XM4 (Figure 24) is a complete computer system that can accept multiple serial devices, has both wired and wireless Ethernet ports, and runs the Linux operating system. It is very low power and is literally the size of a stick of gum. A software bridge could be written to transport the data between the serial ports and the Ethernet port. There are add-on boards available to increase the functionality of the Gumstix also.

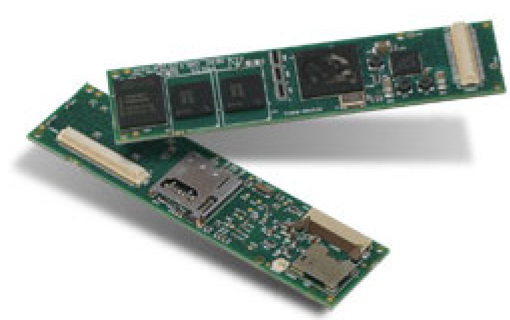

Figure 24: Gumstix Verdex XM4

A bidirectional protocol capable of two-wire operation is needed to transmit data from the TAS to the UUV. The Ethernet protocol is full duplex and high speed but it would normally require four wires in the tow cable. The E-Linx Ethernet Extender (Figure 25) allows Ethernet to be used over two wires. The manufacturer claims the unit will operate at 50mbps at wire runs up to 980 ft, well over the proposed TAS cable scope. The E-Linx extender will auto-negotiate its speed to maintain data integrity, eliminating the risk of data loss. On the tow body side, there would be a Gumstix connected to the Ethernet Extender via the Ethernet port and on the UUV side there would be another Ethernet extender connected to the vehicle's main computer via its Ethernet port. The software bridge would be written to facilitate accessing the data on the UUV side.

Figure 25: E-Linx Two-Wire Ethernet Extender

4.3.2 GPS Hardware

Working with the experts at NavtechGPS we have selected a GPS module and antenna that will work well in this unique application. The NovAtel OEMV1/1G line of GPS engines (Figure 26) offers centimeter-level positioning accuracy with RTK corrections and 2m or greater accuracy unaugmented; and high reliability by using additional satellites in the GLONASS network. With 48+ satellites in the combined GPS-GLONASS networks, performance in high seas will improve as more satellites are visible in the non-blocked portions of the sky. The OEMV1 supports both RS232 and USB interfaces.

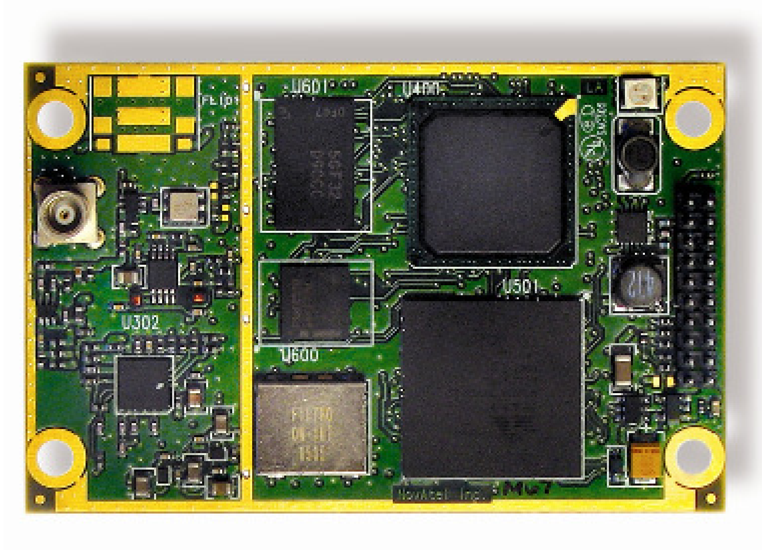

Figure 26: NovAtel OEMV1/1G GPS Module

The recommended antenna is the PCtel WS3951-HR (Figure 27). This antenna has many advantages including high gain, low noise, low power and small size. It also has a high rejection dual SAW filter. This will decrease the risk of interference with the Wi-Fi antenna since they will be in close proximity to each other.

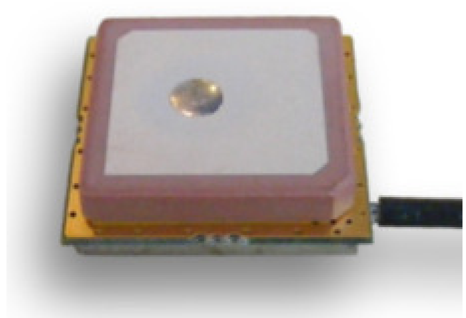

Figure 27: PCtel WS3951-HR

4.3.3 Iridium Satellite

The Iridium 9601 (Figure 28) is an OEM solution designed for embedded systems. It offers global coverage for the short-burst-data (SBD) service. The SBD service allows 340 bytes per message which should be fine for "phone-home" messages containing GPS coordinates and simple status updates. The 9601 interfaces with RS232 and uses a L-band antenna. We have the option of giving the 9601 its own antenna or using combined GPS/Iridium antenna elements in a small form factor with a splitter to separate the Iridium and GPS signals. Advantages for using a splitter are reduced cost and weight due to the reduced size of the packaged antennas.

Figure 28: Iridium 9601 Module

4.3.4 Wi-Fi

The Wi-Fi module chosen for the TAS is actually part of the Gumstix microcontroller. The NetWi-FiMicroSD Add-on board (Figure 29) features a 10/100 wired Ethernet port and a Marvell 88W8385 Wi-Fi module supporting IEEE 802.11b/g. There is also a MicroSD slot allowing up to 4Gb of flash memory to be used by the Gumstix for logging or other file storage needs. We have tested this device in the past and achieved typical performance using the standard dipole antenna.

Figure 29: NetWi-FiMicroSD Add-on Board for Gumstix

We have also performed experiments on increasing the range of the Wi-Fi using COTS amplifiers and antennas. A RFLinx 2400CAE-1W (Figure 30) is a 1-watt amplifier that is connected between the radio and antenna. It uses automatic gain control to only use power when it needs to send or receive, saving energy. Testing performed by BOT showed that by using this amplifier we could achieve up to 1 mile of range over open water.

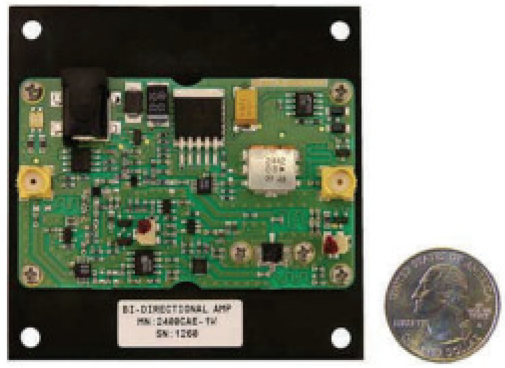

Figure 30: RFLinx 2400CAE-1W Wi-Fi Amplifier

For the fiber optic tow cable option, we could use a USB Wi-Fi module such as the WL-USB-RSMAP (Figure 31). This module has an SMA antenna jack so we could still use the amplifier to increase range.

Figure 31: WL-USB-RSMAP Wi-Fi Module

4.3.5 Power Management

With the use of a small diameter cable, the amount of power that can be sent up the wire to run all of the electronics is very small. This has lead to an in depth look into how much power the electronics located inside of the tow body need and how the necessary power can be provided to them while the tow body is on the surface.

4.3.5.1 Fiber Optic Cable

The hardware to provide power over fiber optic is a JDSU Photovoltaic power converter (Figure 32). This delivers 0.5 watts at voltages ranging between 2 and 12 volts DC. This is not enough to power the hardware located in the tow body at once, however a small battery could be trickle charged between deployments to the TAS. The battery would be sized based on one deployment rather than one whole mission which would greatly reduce its size and weight.

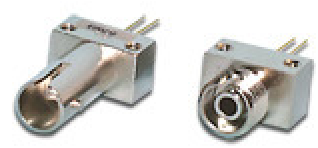

Figure 32: JDSU Photovoltaic Power Converter

To determine the amount of power that would be needed a table of different hardware and power needs was created. A deployment duration of 8 minutes was assumed.

Table 2: Fiber Optic Power Budget

Hardware	Voltage (VDC)	Amperage (mA)	Power (W)	W-hrs
NovAtel GPS	3.3	300	1	0.133
WL-USB-RSMAP WiFi	5	580	2.9	0.39
Ultimate USB	5.0	1500	7.5	1.0
9601 Iridium	5.0	350	1.75	0.23
PCtel Antenna	3.3	7.5	.025	0.003
Total		**2738**	**13.18**	**1.76**

A possible battery that would be used to provide power to the systems located in the tow body is a 7.4 V Li-Po battery with 875 mAh of capacity (Figure 33). This battery weighs only 1.6 oz. and would provide 6.5 W-hrs, over three times the needed capacity.

Figure 33: 7.4V Li-Po Battery

A power control board would be used to regulate the charging and distribution of power to the different system components. If the Axcen fiber optic module was used, this charging circuitry could be incorporated into its circuit board as well. Otherwise, a small PCB incorporating a single chip charging regulator would be built.

4.3.5.2 Coaxial Cable

Since coax is a copper pair, running power up through it to the tow body should be straight forward provided the current is limited to a safe level for the wire gauge. To determine the amount of power that will be required, another power budget for the coax option was created.

Table 3: Coax Power Budget

Hardware	Voltage (VDC)	Amperage (mA)	Power (W)
NovAtel GPS	3.3	300	1
Gumstix	5	300	1.5
NetWifiMicroSD	5	200	1
9601 Iridium	5.0	350	1.75
PCtel Antenna	3.3	7.5	.025
E-Linx Ethernet Ext.	12	200	2.4
Total		**1357.5**	**7.7**

The maximum current required is therefore 1.36 amps. Since the cable is only rated to 0.2 amps we will need to step up the voltage in order to get enough power. The required voltage would need to be 38.5 volts. That is very close to the 36 volts that Bluefin UUVs normally run at. If we ran at this voltage we would put the current 7% over spec but we would not require any additional transformers in the UUV. A small DC-DC converter could take the 36 volts and step it down to the levels required by the electronics. A passive filter inside the tow body would separate out the DC power and the digital signal.

4.3.6 Connectors

4.3.6.1 Fiber Optic Cable

For the fiber optic option, there would need to be two stages of terminations on either end of the cable. First the waterproof jacket and Kevlar strength member would need to be encapsulated to provide strain relief. The two optical fibers would feed through this termination into the dry part of the tow body or UUV where they would each be terminated to fiber optic connectors specified by their mating devices. In order to facilitate cable replacement, the hole for the outer connector would need to be large enough to fit the fiber optic connectors through. This could be quite large depending on the fiber optic connectors chosen.

4.3.6.2 Coaxial Cable

The coax option allows a much simpler termination design than the fiber optic option. On the outside of the tow body there could be a flat section where a standard underwater bulkhead connector is mounted (Figure 34a). The coax cable would be terminated to a mating connector that would serve as strain relief as well (Figure 34b). This would allow the tow body to be simply plugged and unplugged as needed.

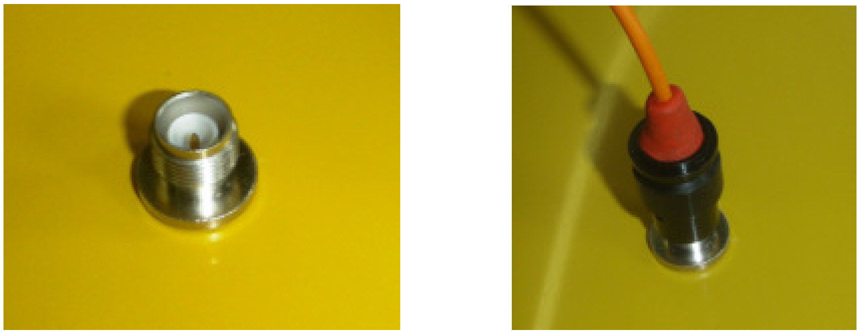

Figure 34: Underwater Coax Connector Mounted on Bulkhead

4.4 Launch and Recovery System

The launch and recovery system was designed to use an innovative reeling system that works underwater and allows for the cable to be directly plugged into a bulkhead without the need of a slip ring. The complete system also needs to be small enough to fit inside the 12 in. inner diameter of a UUV.

4.4.1 Fiber Optics Launch and Recovery System

This design concept (Figure 35) is similar to a spin-cast reel used for fishing. The parts consist of a drum, a bail, gears, and motor.

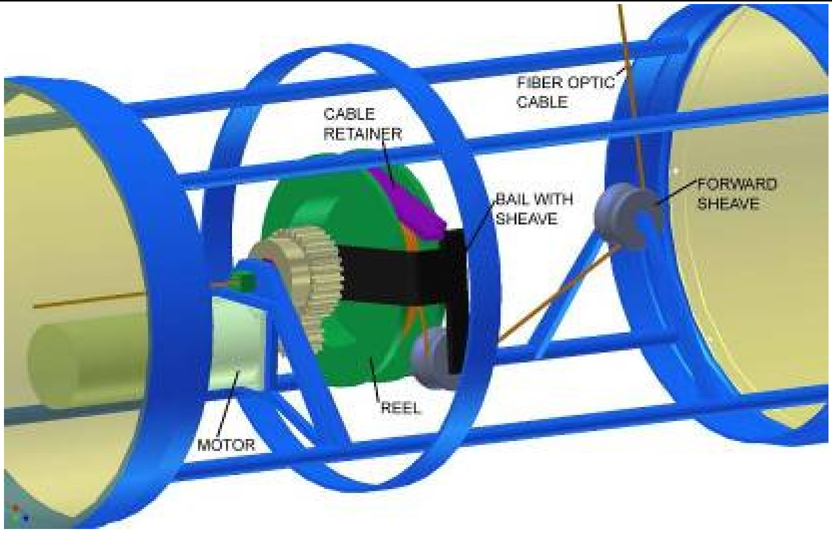

Figure 35: Revised Launch and Recovery System Components

The cable is spun around a fixed spool with a bail type sheave rotating around the spool. This coils the cable around the spool without the spool ever turning. A spring loaded retainer with foam on the inside of it maintains pressure on the cable that is wound on the reel to keep it from loosening and possibly becoming tangled in the event of loss of tension on the tow cable. The reel was designed for 100 ft of the COTS round duplex tow cable. The drum diameter used was 2.5 in. with a drum length of 1in.

The end of the cable that is connected to the bulkhead runs through the middle of the spool until it exits out the back of the reeling system (Figure 36). With this design, there is no slip ring. The total length of the compartment on the UUV would be less than 24in.

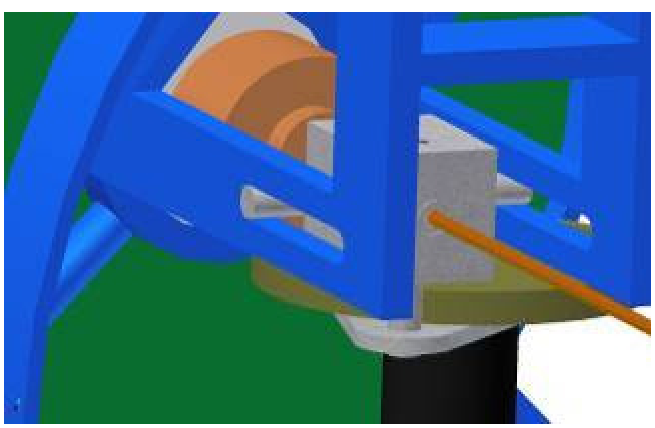

Figure 36: Fiber Optic Cable Exiting Back of Reel

4.4.1.1 Fiber Optic Testing Results

Testing was done on February 24, 2009 to determine if cable twisting occurs during the reeling in out process. A simple reel was made and 30 ft of the fiber optic tow cable was used. The reel diameter was 4.5 in. There was no level wind system. The reel was fixed and could not move. A simple bail was made and was hand driven around the reel. The cable was taped to the reel and straightened out. It was then reeled in. Once fully reeled in, it was found that there was ½ a turn of twist induced in the cable. When the cable was fully let out, the twist went away. This was repeated 10 times with the same results each time.

4.4.1.3 Launch and Recovery Motors

There are four different options being explored for powering the reeling system. Options include a stepper motor, hydraulic motor and HPU, DC rotary actuator, or a modified servo. All of these are designed for underwater use but the depth ratings vary. The smallest and most attractive of these is the modified DA-22 Sub servo (Figure 37) from Volz GmbH of Germany. This servo is designed for travel angles less than 330° but it is easily modified for continuous rotation which is required by the launch and recovery system. The stall torque is 410 oz-in. and continuous torque is 230 oz-in. That translates to between 6Lb and 11Lb of line pull on the drum which is more than we anticipate needing. The size of the servo is 1.75 in. by 2.68 in. by 1 in. It is rated to 100 m depth and it is controlled with the RS422 or RS485 interface.

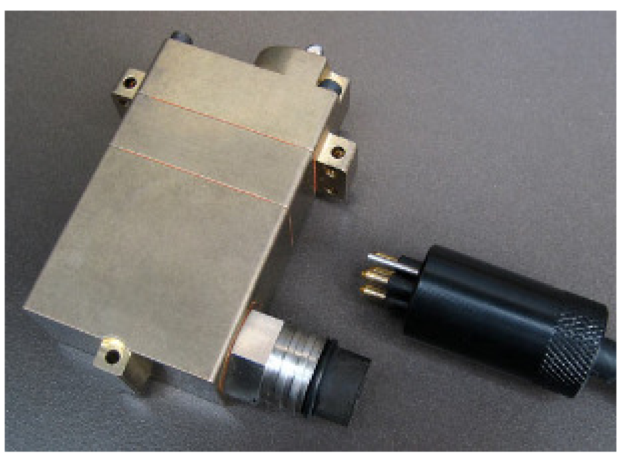

Figure 37: Volz DA-22 SUB Actuator

4.4.2 Coaxial Cable Launch and Recovery System

The small size of the coax cable allows us to consider using an actual spin-cast reel as the foundation for the launch and recovery system. The 0.046 in. diameter coax is only slightly larger than some monofilament fishing lines. After researching large spin-cast reels designed for saltwater use, the Zeebaas ZX27 (Figure 38) was selected for its large size and excellent build quality.

Figure 38: Zeebaas ZX27 Fishing Reel with Coax Cable

The reel is designed to be submerged in a few feet of water for an extended period of time so some waterproofing has already been done, however more work will need to be done to achieve a 100 m rating. The stock drum and pickup sheaves will need to be replaced to satisfy the minimum bend radius of the cable. Also the inner shaft will need a hole machined through it axially to allow the cable to be routed from the drum back to the bulkhead where it will plug in.

The drive motor will be attached to the reel by removing the handle and adding a coupling for the reel to motor shaft interface (Figure 39). Since this drum is smaller than the fiber optic version the line pull figures will be greater even though they were sufficient before.

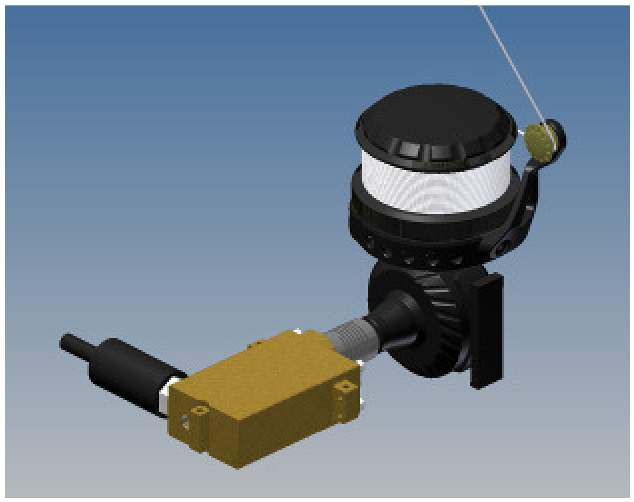

Figure 39: Volz Actuator Coupled with Zeebaas Reel

The small size of both the reel and the motor will allow the total length of the compartment to be as small as the length of the tow body. This is because the small reeling mechanism can fit beneath the tow body instead of taking up space beside it. This compact compartment (Figure 40) can be installed on any 12 ¾" UUV.

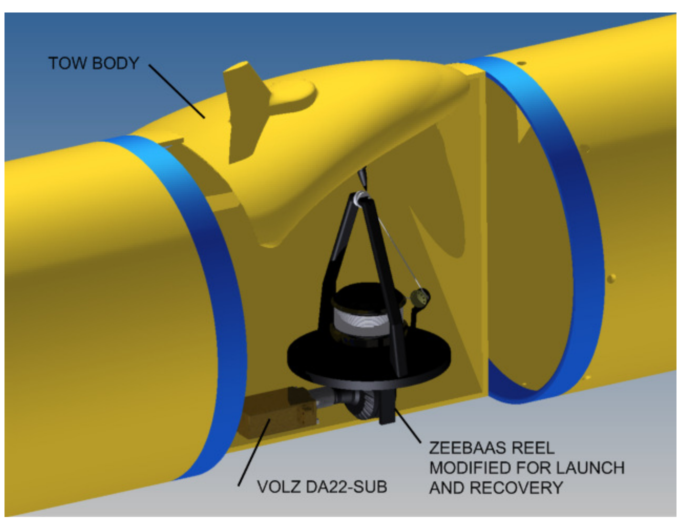

Figure 40: Cutaway View of Coax Launch and Recovery

5.0 SUMMARY

5.1 Conclusions and Recommendations

BOT USA has a wealth of knowledge and experience with tow bodies and unmanned underwater vehicles. Leveraging this expertise, a towed antenna system which meets USN requirements of supporting two-way RF communication and GPS reception for UUVs has been developed.

All systems devised have been designed for reliable use in the marine environment. Component size has been optimized to reduce the impact on the host UUV while performing the operation of RF communication and providing the UUV with a GPS signal. This system will be an inexpensive alternative to the current methods such as Inertial Navigation systems.

For Phase II, it is recommended that the work plan outlined below be adopted. This plan outlines a strategy for the further development, testing, and demonstration of the following full scale prototype system leading to potential product commercialization:

- Operational Tow Body
- Automated launch and retrieval of the tow body from an 12 ¾” UUV
- RF communication between the UUV and a local source
- Iridium satellite for global communications
- Accurate and consistent GPS location of the UUV
- System as small as possible to minimally affect the UUV
- Multiple versions for different diameter UUVs